

Permafrost thawing from different technical systems in Arctic regions

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Abstract. A new three-dimensional model of thermal interaction in a "heat source-and-soil" system is proposed to study the process of permafrost degradation from various engineering facilities operating in the Arctic regions, taking into account a number of physical and climatic factors that affect the heat distribution. On the base of the proposed model, a software complex was developed to predict long-term dynamics of permafrost thawing in the upper layer of soil, and this approach was used in the design of 11 northern Russian oil and gas fields and is in a good agreement with numerical results and experimental data. Numerical calculations are presented for illustration the possibility of carrying out long-term forecasts for the determination of permafrost zone defrosting during operation of production wells in northern oil and gas field.

1. Introduction

Permafrost soils, which conserve a negative temperature deeper than the active layer thickness (ALT), takes about 25 % of the globe land [1–6]. In Russia, permafrost zones are extremely important in view to both oil and gas field exploitation and a general development of the Arctic. Thawing of iced soils due to warming of the climate, or various industrial impacts, will be followed by subsidence of the earth's surface and dangerous permafrost geological processes, called thermokarst, and as a result, it leads to disruptions and accidents [7–11].

The irrational design and functioning of cluster sites in Arctic oil and gas fields leads to significant additional and financial costs, which under the conditions of low oil prices reduces the profitability of development and operation of new and existing oil and gas fields. In this regard, it is relevant to reduce the cost of designing and optimizing the operation of new and functioning oil and gas fields. Therefore the problem of reducing the intensity of thermal interactions in the "heat source – permafrost" zones has a particular importance for solving problems of energy saving, environmental protection, safety, cost savings and enhance operational reliability of various engineering structures.

Further, we consider a three-dimensional model which allows to describe heat distribution in upper layers in permafrost soils with taking into consideration not only most significant climatic factors (seasonal changes in temperature and intensity of solar radiation due to geographic location of the field) and physical factors (different thermal characteristics of non-uniform ground that change over the time) [12] but also engineering construction features of the production wells [13]. This model



may be used for simulations including other types of technical systems such as ripraps, tanks, pipelines, flare systems and others [14].

2. Mathematical model and basic heat flows

First, let consider heat exchange on a flat ground surface directly illuminated by the sun. Let the initial time be $t_0=0$, and the ground is a box Ω and has a temperature $T_0(x,y,z)$ (Figure 1). The computational domain is a three-dimensional box, where x and y axes are parallel to the ground surface and the z axis is directed downward. We assume that the size of the region Ω is defined by positive numbers L_x, L_y, L_z : $-L_x \leq x \leq L_x, -L_y \leq y \leq L_y, -L_z \leq z \leq 0$. To simulate the propagation of heat in this volume the following mathematical model is suggested.

Heat Transfer Equation with a Phase Transition

Let $T = T(t,x,y,z)$ be soil temperature at the point (x,y,z) at the time moment t . The main heat flow associated with climatic factors on the surface $z = 0$ is shown in Figure 1.

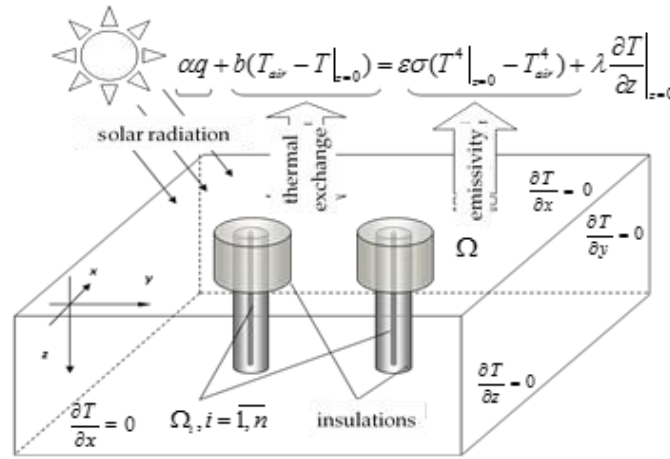


Figure 1. An area for simulation

We will consider an equation of the contact (diffusion) heat conductivity with inhomogeneous coefficients is used as a basic mathematical model with including localized heat of phase transition – an approach to solve the problem of Stefan type, without the explicit separation of the phase transition. The heat of phase transformation is introduced with using Dirac δ -function as a concentrated heat of phase transition in the specific heat ratio. The obtained discontinuous function then “shared” with respect to temperature, and does not depend on the number of measurements, phases, and fronts. Thus, the modeling of thawing in the soil is reduced to the solution in Ω of the equation

$$\rho(c_v(T) + k\delta(T - T^*)) \frac{\partial T}{\partial t} = \text{div}(\lambda(T) \text{grad } T) \quad (1)$$

where:

$\rho = \rho(x,y,z)$ is density [kg/m³],

$T^* = T^*(x,y,z)$ is temperature of phase transition,

$c_v(T) = \begin{cases} c_1(x,y,z), & \text{for } T < T^*, \\ c_2(x,y,z), & \text{for } T > T^*, \end{cases}$ is specific heat [J/kg K],

$\lambda(T) = \begin{cases} \lambda_1(x,y,z), & \text{for } T < T^*, \\ \lambda_2(x,y,z), & \text{for } T > T^*, \end{cases}$ is thermal conductivity [W/m K],

$k = k(x,y,z)$ is specific heat of phase transition, δ is Dirac δ -function.

The coefficients included in equation (1) may vary at different points in the computational domain Ω because of heterogeneity of the soil and possible presence of engineering structures.

Boundary Conditions

The ground surface $z = 0$ is the main zone of formation of the natural thermal fields. On this surface the equation of balance of flows is used as a boundary condition, with taking into account the main climate factors: air temperature and solar radiation. On the surfaces Ω_i , bounding the objects in Ω , a set of the temperatures $T_i(t)$, $i = 1, \dots, n$, is given. The bottom surface ($z = -L_z$) and lateral faces ($x = \pm L_x$, $y = \pm L_y$) of the parallelepiped Ω (Figure 2) is assumed that the heat flux is equal to zero.

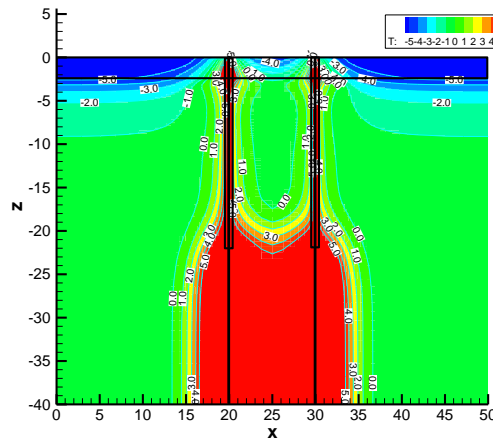


Figure 2. Thermal field around the wells for the moment when the left well has stopped

Thus it is necessary to solve equation (1) in the area Ω with initial condition

$$T(0, x, y, z) = T_0(x, y, z) \quad (2)$$

and boundary conditions

$$\alpha q + b(T_{air} - T|_{z=0}) = \varepsilon \sigma (T_{z=0}^4 - T_{air}^4) + \lambda \frac{\partial T}{\partial z} \Big|_{z=0}, \quad (3)$$

$$T|_{\Omega_i} = T_i(t), \quad i = 1, \dots, n, \quad (4)$$

$$\frac{\partial T}{\partial x} \Big|_{x=\pm L_x} = 0, \quad \frac{\partial T}{\partial y} \Big|_{y=\pm L_y} = 0, \quad \frac{\partial T}{\partial z} \Big|_{z=-L_z} = 0. \quad (5)$$

Condition (2) determines the initial distribution of soil temperature at the time moment from which we plan to start the numerical calculation. Condition (3) is obtained from the balance the heat fluxes at the ground surface $z = 0$. Conditions (4) appear in the case if in the ground there are different objects, which temperature is different from the surrounding soil.

3. Numerical results

On the base of ideas in [15–17] a finite difference method is used with splitting by the spatial variables in three-dimensional domain to solve the problem (1)–(5). We construct an orthogonal grid, uniform, or condensing near the ground surface or to the inner surfaces. The original equation for each spatial direction is approximated by an method to solve a system of linear differential algebraic equations

is used. Heterogeneity of the coefficients in (2) is taken into account by the corresponding heat flux at each point of the difference grid. The grid is constructed in such a way that grid points take place in layers of insulating materials or in the considered engineering constructions (for example, in a concrete slab in riprap layers). In addition, if an engineering construction is a heat source (for example, a well), we introduce dummy nodes of the inner boundary, that allows to accurately determine the position and intensity of heat generated by this source.

A similar approach is used in the study of thermal fields on the day surface from an underground pipeline [18] and a geothermal system [19] without of the phase transition.

Note, that for the considered problems an analytical methods of investigation, such as [20], is difficult and unavailable, but, in a case it is possible to construct an exact solution [21], applicable for numerical methods verification. Complexity of analytical methods application is also related with nonlinear boundary condition (3), which application is determined in [22–24].

On the base of the model (1)–(5) a program complex «Wellfrost» is developed, which was approved for 11 oil and gas fields located in the permafrost zone. In comparing of the numerical and experimental data it was observed that boundary of permafrost thawing from an injection well, operated for 3 years, coincides in approximation up to 5% with experimental data. This fact allows to suggests that the developed algorithm and software package «Wellfrost» may serve to test various other techniques. In the following we present some numerical results for some Russian northern oil and gas fields.

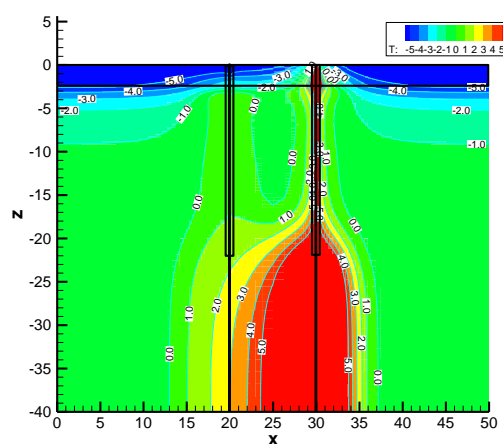


Figure 3. Thermal field around the wells after 1 year after the left well has stopped.

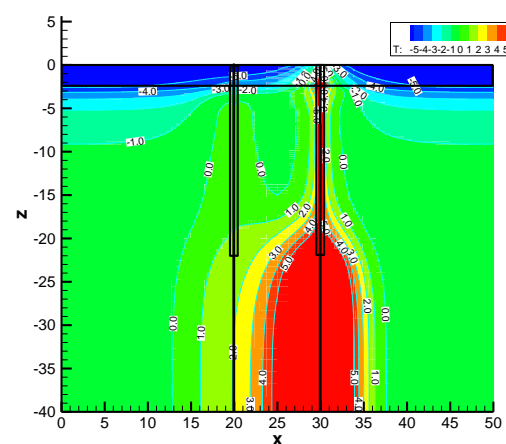


Figure 4. Thermal field around the wells after 2 years after the left well has stopped.

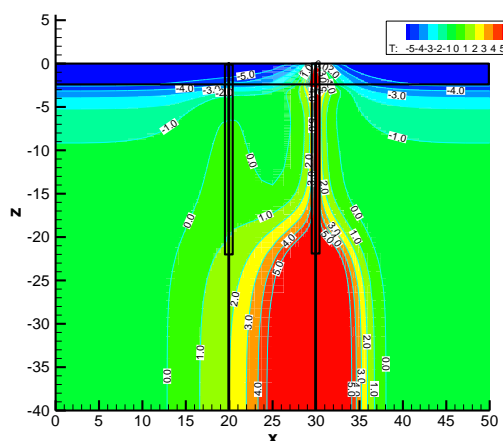


Figure 5. Thermal field around the wells after 3 years after the left well has stopped.

Let consider a system of two wells with thermal insulations in the upper layer in the deep to 12 m. The wells are drilled in a loam soil with the temperature -0.7°C . The well diameter is 0.18 m, distance between the wells is 10 m. The oil heated up to 45°C leads to the soil thawing around the wells. In Figure 2 distribution of temperature in the vertical slice along the wells is shown for 6 years of exploitation. The fronts of thawing from the wells (zero isotherm) in the bottom of the area are jointed. In the upper layers of soils one can see the ALT (approx. 2 m) and the part conserved frozen and stable due to the thermal insulation of the wellheads. The figures 3–5 show the cooling process when the left well has stopped. The zero isotherm turns back to the left wellhead. The front of thawing movement is present in figures 6 and 7. The numeration of lines corresponds to the years of exploitation. The results of computations allow to estimate of thermal influence of the inserted engineering constructions and to preven some damages caused by permafrost thawing and degradation.

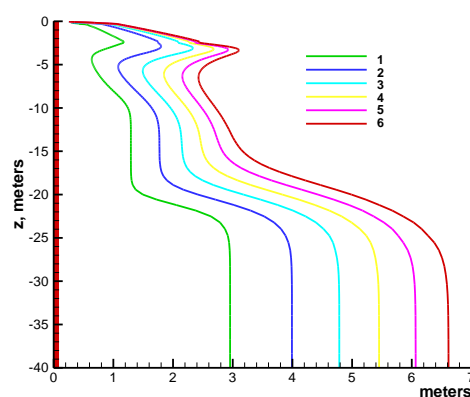


Figure 6. Front of thawing movement during 6 years from the well in exploitation.

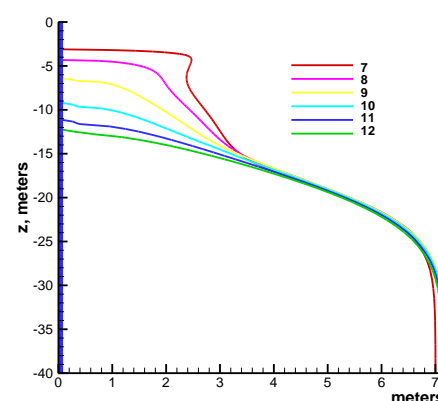


Figure 7. Front of thawing movement during 6 years to the stopped and cooling well.

4. Conclusion

1. Based on the mathematical model, a complex of computational codes is developed with a cloud interface for numerical three-dimensional modeling of non-stationary thermal fields in the upper layer of permafrost soils from various technical systems located in the northern oil and gas field.

2. Numerical simulations for well sites allow to improve safety and efficiency of northern oil and gas fields due to an optimal location of wells and other technical systems in this area and have a significant economic effect during the design stage. For example, in 2012, the simulations allowed to reduce by 50% the size of a well pad for placing the producing wells for one of the Russian northern oil and gas fields.

3. A basic feature of the developed package of computational codes is a possibility of adaptation of the model parameters to the selected geographical location of the area under investigation. For this purpose, an original iterative algorithm is developed that allows to take into account both the varying thickness of the snow, and the number of sunny days per year, and the feature of the topsoil layer, etc.

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